

## **MULTI-CHANNEL LASER INTERFEROMETRIC METHOD AND APPARATUS FOR DETECTION OF ULTRASONIC MOTION FROM A SURFACE**

### **Background of Invention**

**[0001]** The present invention relates to laser interferometric method and apparatus with large collecting aperture for measuring motion from a surface. The invention is particularly directed toward detecting small displacement of a surface, and more particularly, an optically scattering surface, of a workpiece subjected to ultrasound, where the workpiece does not need to be accurately positioned.

**[0002]** The detection of phase modulation of an optical wave is important for various field of application where optical beams are used to detect the small motion of an object. This is the case of laser detection of ultrasound and transient body motion such as those produced by the sudden absorption of a laser pulse. The technique based on laser generation and detection, known as Laser Ultrasonic (LU) or Laser Based Ultrasonic (LUB), allows for remote and non-contact detection and generation of ultrasound. Laser ultrasonics can thus be advantageously used for inspection at high temperature, on-line and during process. Most of the industrial application of laser ultrasonics involves the inspection of an "optically rough" surface. The probed surfaces being optically rough, the ultrasonic information is thus encoded in an optical beam with speckle. A suitable interferometric technique should integrate effectively over the large speckle field and provide an output signal independently of the speckle nature the collected light. Adequate sensitivity requires an interferometric technique which has a large effective light gathering efficiency. Interferometric techniques based on plane wave reference using heterodyne scheme (U.S. Pat. No. 4,633,715) or quadrature scheme (U.S. Pat. No. 5,404,224) are only effective if the two interfering beams (the reference beam and the object beam reflected from the sample) are plane waves. For object with rough surfaces reflecting a speckled beam, the plane-wave interference requirement means that only a single speckle should be selected

from the object beam for high efficiency interference. Single speckle selection means that the collecting aperture is very small and thus these interferometers have very low sensitivity on rough surfaces. Instead of single speckle detection, these interferometers can be optimized for collecting few speckles in order to increase the amount of collected light, but unfortunately the sensitivity is not directly improved by the higher amount of collected light because the random phase distribution of speckles reduces the interference efficiency.

**[0003]** In various U.S. patents, laser interferometric schemes for detection on rough surfaces have been described. These schemes are characterized by their large étendue parameter. These laser interferometric schemes are based on confocal Fabry-Pérot (U.S. Pat. No. 4,966,459) or adaptive photorefractive interferometer (U.S. Pat. No. 5,131,748)

**[0004]** For industrial application, the reduction in the need for accurate object positioning is as critical as to have a high sensitivity on a rough surface. In most industrial application, the positioning of the sample is not controlled accurately. An optical system with high sensitivity but high requirement for target positioning will lead to an overall system with poor sensitivity, where good signals are acquired only sporadically when the sample moves through the optimum position. To better control the sample position may not be easily possible or may highly increase the overall cost of the inspection system, making the system not affordable and limiting its field of application. Often a compromised is used by detuning the system in order to get more uniform performance over a larger range of sample positions, at the expense of the maximum sensitivity.

**[0005]** Accordingly, it is one of the principle objects of the invention to provide a method and apparatus for optically detecting ultrasonic transient motion from scattering surface, having a high sensitivity, a large gathering optics as well as a large depth-of-field. The depth-of-field (DOF) is defined

as the variation in the stand-off distance that causes a reduction by a factor two from the maximum sensitivity of the optical system.

### **Summary of Invention**

**[0006]** In accordance with a first aspect of the invention, there is thus provided a multi-channel laser interferometric method for measuring the displacement of a surface of a material subjected to ultrasound, which comprises :

- generating a laser beam having a predetermined intensity;
- dividing the laser beam into a reference beam and a probe beam having respective intensities representing minor and major fractions of the predetermined intensity;
- passing the probe beam through an optical lens to focalize the probe beam onto the surface of the material subjected to ultrasound, thereby scattering same;
- expanding the reference beam;
- combining the scattered probe beam collected by said optical lens with said expanded reference beam to obtain an optical fringe signal;
- receiving said optical fringe signal on at least one array of photodetectors, wherein said optical fringe signal fully covers said array and each photodetector of the array defines a channel, having a given aperture smaller than the aperture of said optical lens to receive a portion of said optical fringe signal and converting said portion of said optical fringe signal into an electrical signal;
- processing for each channel said electrical signals through circuitry means;
- summing electrically said processed signals to extract an output signal correlated to the motion of said surface.

**[0007]** According to a first embodiment, processing comprises first filtering the electrical signals, then squaring the filtered signals.

**[0008]** According to a second embodiment, processing comprises first filtering the electrical signals, then rectifying the filtered signals.

- [0009] According to a further embodiment of the method, it further comprises linearly polarizing the scattered probe beam collected by the optical lens, circularly polarizing the expanded reference beam, combining the linearly polarized scattered probe beam with the circularly polarized expanded reference beam to obtain two optical fringe signals having a phase shift of  $90^\circ$  and receiving the first and second optical fringe signals on two arrays of detectors, the two arrays of detectors being identical, two detectors of the corresponding channels of the arrays generating two in-quadrature electrical signals, the electrical signal pairs being then processed together through the circuitry means.
- [0010] According to a first embodiment, the step of processing comprises first dividing and filtering the in-quadrature signal pairs to separate each signal into a high-frequency signal and a low-frequency signal, then for each signal pair, generating two signals by cross-multiplication between the low-frequency signal pair and the high-frequency signal pair, and differentiating the two signals.
- [0011] According to a second embodiment, the step of processing comprises first dividing and processing the in-quadrature signal pairs to separate each signal into the original signal and its derivative signal, then for each signal pair, generating two signals by cross-multiplication between the original signal pair and the derivative signal pair, and differentiating the two signals.
- [0012] According to a third embodiment, the step of processing comprises first high-pass filtering the signal pairs, then for each signal pair, summing the two signals obtained by squaring of each signal of the signal pair.
- [0013] According to a quarter embodiment, the step of processing comprises first high-pass filtering the signal pairs, then for each signal pair, summing the two signals obtained by rectification of each signal of the signal pair.
- [0014] According to a further embodiment of the method, the scattered probe beam and the expanded reference beam have crossed polarization, and it further comprises dividing each of the scattered probe beam and the expanded

reference beam in two optical signals having a  $180^\circ$  phase difference, the combining of the optical signals resulting in four optical fringe signals having  $-90^\circ$ ,  $0^\circ$ ,  $90^\circ$  and  $180^\circ$  relative phase differences; the step of receiving further comprises:

- receiving the four optical fringe signals on four arrays of detectors, the four arrays of detectors being identical, each set of four detectors of a corresponding channel generating two in-quadrature pairs of out-of-phase electrical signals,
- subtracting each out-of-phase electrical signals to obtain a pair of differential in-quadrature electrical signals for each channel, the pairs of differential in-quadrature electrical signals being processed together through the circuitry means.

**[0015]** According to a further embodiment of the method, it further comprises frequency shifting the reference beam, the optical fringe signal resulting from combining the scattered probe beam with the expanded shifted reference beam being an heterodyne optical fringe signal; and the step of processing comprises demodulating each electrical signal for each channel by removing the frequency shift using heterodyne demodulation techniques.

**[0016]** In accordance with a second aspect of the invention, there is provided a multi-channel laser interferometric apparatus for measuring the motion of a surface of a material subjected to ultrasound, which comprises:

- a laser source for generating a laser beam having a predetermined intensity;
- a beam splitter for dividing said laser beam into a reference beam and a probe beam having respective intensities representing minor and major fractions of said predetermined intensity;
- an optical lens disposed for focalizing said probe beam onto the surface of said material subjected to ultrasound, thereby scattering same;
- a beam expander expanding said reference beam;
- combining means for combining the scattered probe beam with said expanded reference beam to obtain an optical fringe signal;

- receiving means with at least one array of detectors for receiving said optical fringe signal on, wherein the optical fringe signal fully covers the array, and each detector, defining a channel, has a given aperture smaller than the aperture of said optical lens to receive a portion of said optical fringe signal and convert said portion of said optical fringe signal into an electrical signal;
- circuitry means for processing for each channel said electrical signals and summing said processed signals to extract an output signal correlated to motion of the surface.

[0017] According to a first embodiment, the array of detectors is a linear array of detectors.

[0018] According to a second embodiment, the array of detectors is a two-dimensional array of detectors

[0019] According to a third embodiment, circuitry means comprise filtering means for filtering the electrical signals and squaring means for squaring the filtered signals.

[0020] According to a quarter embodiment, circuitry means comprise filtering means for filtering the electrical signals and rectifying means for rectifying the filtered signals.

[0021] According to a further embodiment, the apparatus further comprises polarizing means for circularly polarizing the expanded reference beam, and the combining means comprise a polarizing beam splitter for combining the linearly polarized scattered probe beam with the expanded circularly polarized reference beam to obtain two optical fringe signals having a phase shift of  $90^\circ$ ; the receiving means comprise two identical arrays of detectors for receiving the optical fringe signals on, the two detectors of a same channel of each array generating a pair of in-quadrature electrical signals, the pairs of in-quadrature electrical signals being then processed together by the circuitry means.

**[0022]** According to a further embodiment, the apparatus further comprises polarizing means for setting the polarization of the expanded reference beam orthogonal to the polarization of the probe beam; dividing means to divide each of the polarized scattered probe beam and the expanded orthogonally polarized reference beam into a first and a second signals; an optical retardation device in one of the first or second optical signals to obtain a phase shift of  $90^\circ$  between the first and second optical signals; and the combining means comprise two polarized beam splitters for combining the two orthogonally polarized components of the first and second optical signals, each into two optical fringe signals having a  $180^\circ$  phase difference; resulting in four optical fringe signals having  $-90^\circ$ ,  $0^\circ$ ,  $90^\circ$  and  $180^\circ$  relative phase differences; the receiving means comprise four identical arrays of detectors for receiving the four optical fringe signals, each set of four detectors of a corresponding channel generating two pairs of out-of-phase electrical signals; the circuitry means further comprise subtracting means for subtracting each of the out-of-phase electrical signals to obtain a pair of differential in-quadrature electrical signals for each said channel, the pairs of differential in-quadrature electrical signals being then processed together.

**[0023]** According to a further embodiment, the apparatus further comprises a frequency shifting device for frequency shifting the reference beam by a given frequency, the frequency shifted reference beam being then expanded, and the combining means combine the scattered probe beam with the expanded frequency shifted reference beam to obtain an heterodyne optical fringe signal, the heterodyne optical fringe signal being received by the receiving means the circuitry means comprise demodulation means for processing for each channel the heterodyne electrical signals through demodulation by removing the frequency shift using standard heterodyne demodulation techniques, the output signal obtained by summing the processed signals being proportional to the displacement of the surface.

[0024] According to a further embodiment, the apparatus further comprises a multi-mode optical fiber and coupling means for coupling the laser beam into the optical fiber, and a partially reflecting coating at the optical fiber end enables dividing the laser beam into the reference beam and the probe beam; the optical lens for focalizing the probe beam onto the surface of the material is disposed at the end of the optical fiber, and refocuses the scattered probe beam into the optical fiber; the receiving means comprise at least one two-dimensional array of detectors and a second optical lens for focusing on the array of detectors the multi-mode optical beam exiting though the entrance face of the multi-mode fiber and corresponding to the mixing between the scattered beam and the partially reflected beam.

### **Brief Description of Drawings**

[0025] Further features and advantages of the invention will become more readily apparent from the following description of preferred embodiments with reference to the appended drawings, in which:

[0026] Figure 1 is a schematic diagram of a Mach-Zehnder-type interferometric apparatus according to the prior art;

[0027] Figure 2A is a schematic diagram of a multi-channel laser interferometric apparatus according to a first embodiment of the invention;

[0028] Figure 2B is a variant of the embodiment shown in Figure 2A which includes a differential detection scheme;

[0029] Figure 3 is a schematic diagram of a second embodiment of a multi-channel laser interferometric apparatus which includes heterodyne modulation;

[0030] Figure 4A, 4B and 4C are schematic diagrams of a multi-channel laser interferometric apparatus according to other embodiments of the invention;



- [0031] Figure 5 is a schematic diagram of circuitry means for processing of signals in the embodiments shown in Figures 2A and 2B and for delivering an output signal proportional to displacement;
- [0032] Figure 6 is a schematic diagram of circuitry means for processing of signals in the embodiments shown in Figures 2A and 2B and for delivering an output signal proportional to velocity;
- [0033] Figure 7 is a schematic diagram of circuitry means for processing of signals in the embodiments shown in Figures 2A and 2B and for delivering an output signal proportional to displacement energy;
- [0034] Figure 8 is a schematic diagram of a variant of the signal processing shown in Figure 7 which delivers an output signal correlated to displacement;
- [0035] Figures 9A and 9B are schematic diagrams of circuitry means for processing of signals in the embodiments shown in Figures 4A, 4B and 4C and for delivering an output signal correlated to displacement;
- [0036] Figure 10 is a schematic diagram of circuitry means for processing of signals in the embodiments shown in Figures 3 and for delivering an output signal proportional to displacement;

### Detailed Description

- [0037] Fig 1 schematically illustrates a Mach-Zehnder-type interferometric apparatus according to the prior art for measuring the displacement of a surface of a material subjected to ultrasound. A laser 10 is used to generate a laser beam 11. A polarizing beam splitter 12 is used to divide the laser beam 11 into a probe beam 18 and a reference beam 19 having respective intensities representing minor and major fractions of the intensity of the laser beam 11. The probe beam 18, reflected by the polarizing beam splitter 12, then passes through a quarter wave plate 14 whereby probe beam 18 is circularly polarized and focused by mean of a lens 15 onto the surface of a workpiece 17. The object beam 21, corresponding to the probe beam back-reflected by the workpiece and collected by the lens 15, is linearly polarized and is

directed toward a polarizing beam splitter **23**. The reference beam **19** passes a quarter wave plate **16** whereby reference beam is circularly polarized. The reference beam is picked-up by mirrors **20** and **22** and directed onto the polarizing beam splitter **23** which is set a  $45^\circ$  of the linear polarization axis of the object beam **21**. The linearly polarized object beam **21** and the circularly polarized reference beam **19** are mixed and divided by the polarizing beam splitter **23** into two interference signals **24** and **25** which are detected by detectors **26** and **27**. The electronic fringe signals **28** and **29** that are generated by the detectors exhibit a  $90^\circ$  phase difference. The quadrature signals are processed by a processing circuitry **30** to deliver an output signal **31** correlated to the motion of the surface. In this apparatus, a large collecting optical lens **15** enables to collect more scattered light and thus to enable an higher sensitivity of the measurement. But a large collecting optical system that relays the gathered light on a small size photodetector **26, 27**, will quickly loose its gathering effectiveness when the interrogated surfaces moved away from the designed distance corresponding to the maximum light gathering. Furthermore, the collected scattered light is not efficiently used because of the random phase distributions of the speckles. Indeed, the gathering of large number of speckles on a single detector increases the average power collected but unfortunately it also averages out the phase information, strongly reducing its effectiveness.

[0038] Accordingly, it is one of the principle objects of the invention to provide a method and apparatus for optically detecting transient motion from scattering surface, having a large gathering optics, as well as a large depth-of-field. The interferometric apparatus according to the invention comprises a laser source for generating a laser beam having a predetermined intensity, a beam splitter for dividing the laser beam into a reference beam and a probe beam having respective intensities representing minor and major fractions of said predetermined intensity. It further comprises an optical lens disposed for focalizing the probe beam onto the surface of the material subjected to ultrasound, thereby scattering same, and a beam expander for expanding the

reference beam. It also comprises combining means for combining the scattered probe beam with the expanded reference beam to obtain an optical fringe signal and receiving means with at least one array of detectors for receiving the optical fringe signal on, wherein the optical fringe signal fully covers the array. Each detector, defining a channel, has a given aperture smaller than the aperture of the optical lens to receive a portion of the optical fringe signal and convert this portion of the optical fringe signal into an electrical signal. It further comprises circuitry means for processing for each channel the electrical signals and summing the processed signals to extract an output signal correlated to motion of the surface.

[0039] The optical arrangement according to the invention thus implements a compact multi-channel interferometer that enables a large aperture interferometer. The signals of each interferometric channels are coherently added in order to generate the large aperture interferometric signal.

[0040] FIG 2A illustrates a first preferred embodiment of the optical arrangement according to the invention. According to the invention, arrays of detectors 39 and 40 are used instead of single element detectors. These arrays may be linear arrays or two-dimensional arrays. Similarly to FIG 1, the laser beam 11 is split in a probe beam 18 and a reference beam 19 using the beam splitter 12. As in the set-up of FIG 1, the beam splitter 12 is a polarizing beam splitter. Non-polarizing beam splitter can be used, but polarization of laser beam must be aligned properly and polarizer must be added in the setup in order to clean the polarization of the scatter from the sample. The reference beam is expanded by the beam expander 32 such as to fully fill the active area of the array of detectors 39 and 40. The object beam 35, corresponding to the probe beam back-reflected by the workpiece and collected by the lens 15, is linearly polarized and is directed toward combining means 36. In the arrangement of FIG 2A, the combining means comprise a polarizing beam splitter 36 for combining the linearly polarized scattered probe beam with the expanded circularly polarized reference beam 34 to obtain two optical fringe

signals **37** and **38** having a phase shift of  $90^\circ$ . The optical fringe signals **37** and **38** are detected by the arrays of detectors **39** and **40**. By using identical array of detectors that are positioned to look at the same optical fringe, then each pair of electrical fringe signals from the arrays of electrical fringe signals **41** and **42** corresponds to the same optical fringe and each pair exhibits a  $90^\circ$  phase difference between signals. The pair of quadrature signals defines a channel and each pair of signals is similarly processed by a parallel processing circuitry **43**. The multiple processed signals **44** are then summed by a summing amplifier **45** in order to give an average output signal **46**. The average output signal **46** can be proportional to displacement, velocity or displacement energy of the workpiece surface, depending on the processing scheme used for each channel, as it will be explained further in reference to FIG 5, 6, and 7.

[0041] FIG 2B illustrates a variant of the first embodiment shown in FIG 2A which includes a differential detection scheme. The reference beam **19** passes through a half wave plate **48** whereby reference beam is linearly polarized and orthogonal to the object beam polarization **35**. In this embodiment, the object beam **35** and the crossed polarized reference beam **47** are first divided by dividing means, as a beam splitter **49**, into two optical signals **50** and **51**. One of the optical signals, the optical signal **50** in FIG 2B, passes through a quarter wave plate **52** which has its optical axis oriented along the polarization axis of the optical signal **50**, resulting in a  $90^\circ$  phase shift between the two orthogonal polarizations. In this embodiment, the combining means comprise two polarizing beam splitters **53a** and **53b** and the receiving means comprise four arrays of detectors **56a**, **56b**, **57a** and **57b**. The partially transmitted object beam and reference beam **50** and **51** are made to interfere along the two polarization directions of the polarizing beam splitters **53a** and **53b**, respectively. The polarizing beam splitters **53a** and **53b** are oriented at  $45^\circ$  to the plane of the drawing. The resulting optical fringe signals along the two polarizations of the polarizing beam splitters phase **53a** and **53b** are received by the four arrays of detectors **56a**, **56b**, **57a** and **57b**. The four arrays of

detectors **56a**, **56b**, **57a** and **57b** are identical, each set of four detectors of a corresponding channel generating two in-quadrature pairs (**58a**, **59a**), (**58b**, **59b**) of out-of-phase electrical signals. These signals **58a**, **58b**, **59a** and **59b** are sent to respective arrays of differential amplifiers **60a** and **60b** for subtracting each said out-of-phase electrical signals to obtain a pair of differential in-quadrature electrical signals **61a**, **61b** for each said channel, said pairs of differential in-quadrature electrical signals being processed together through the circuitry means **62**. The multiple processed signals **63** are then summed by the summing amplifier **45** in order to give an average output signal **65**. This optical arrangement uses a balanced detection scheme that is very advantageous when noisy lasers are used. With balanced detection, the common-mode noise that is identical for each detector is rejected by the subtraction process. Intensity noise from the laser is a source of common-mode noise and it can be effectively suppressed by the balancing, allowing the use of lower cost noisy laser without reduction in performance.

[0042] FIG 3 illustrates a second embodiment according to the invention, in which the quadrature detection scheme is replaced by an heterodyne detection scheme. Similarly to FIG 2, the laser beam **11** is split in a probe beam **18** and a reference beam **67**. A frequency shifting device **68**, such as a Bragg cell, is driven by a single frequency oscillator **66** producing a frequency shift at  $f_B$  of the reference beam **67**. After frequency shifting, the reference beam is expanded by the beam expander **32** such as to fully fill the active area of the array of detector **71**. The linearly polarized object beam **35** and the linearly polarized frequency shifted reference beam **67** are mixed by the beam splitter **69** and the heterodyne optical fringe signal **70** is detected by the array of detector **71**. The heterodyne signals **72** are processed by a parallel processing circuitry **75**. The multiple processed signals **76** are then summed by a summing amplifier **45** in order to give an average output signal **78** proportional to displacement of the workpiece surface, as it will be detailed further, in reference to FIG 10. This heterodyne scheme has the advantage of reducing the requirement on the laser quality in order to still achieve sensitive

measurements. Indeed, the intensity noise spectrum of a laser generally exhibits much higher noise at lower frequency than at higher frequency. The noise spectrum often follows a 1/frequency dependency and with the heterodyne scheme, the frequency shifting effectively shifts the signal to higher frequency where the laser noise is lower. Compared to the balanced quadrature scheme, where intensity noise is rejected through balanced detection, this heterodyne scheme only requires a single detector array instead of four detector arrays as shown in FIG 2B.

[0043] FIG 4A illustrates a third preferred embodiment according to the invention, in which the quadrature detection scheme is performed statistically thanks to the random distribution of speckles. Similarly to FIG 2, the laser beam 11 is split in a probe beam 18 and a reference beam 79. The reference beam is expanded by the beam expander 32 such as to fully fill the active area of the array of detector 82. The linearly polarized object beam 35 and the linearly polarized reference beam 79 are mixed by the beam splitter 80 and the optical fringe signal 81 is detected by the array of detector 82. The signals 83 are processed by a parallel processing circuitry 84. The multiple processed signals 85 are then summed by a summing amplifier 45 in order to give an average output signal 86 correlated to displacement of the workpiece surface. The parallel processing circuitry 84 process each signal independently and it can be based on either the square demodulation, as explained below in reference to FIG 9A or the rectification demodulation, as explained below in reference to FIG 9B. This embodiment minimizes the complexity of the system. Only a single detector array is needed and the critical alignment that was required with optical arrangements shown in FIG 2A and FIG 2B, in order to achieved quadrature between signal pairs, is no longer needed.

[0044] FIG 4B illustrates a first variant of the third embodiment shown FIG 4A which includes two arrays of detectors 82 and 88, making use of all the light available. Similarly to FIG 4B, The linearly polarized object beam 35 and the linearly polarized reference beam 79 are mixed by the beam splitter

80. The optical fringe signals 81 and 87 are detected by the array of detectors 82 and 88. The signals 83 and 89 are processed by a parallel processing circuitry 90. In this embodiment the number of signals is doubled compared to the previous embodiment shown FIG 4A. Similarly to the previous embodiment shown FIG 4A, the parallel processing circuitry 90 process each signal independently and it can be based on either the square demodulation, as explained below in reference to FIG 9A, or the rectification demodulation, as explained below in reference to FIG 9B. Because each signal are processed independently, there is no accuracy requirement regarding the relative positioning of the arrays of detectors 82 and 88. The multiple processed signals 91 are then summed by a summing amplifier 45 in order to give an average output signal 92 correlated to displacement of the workpiece surface.

[0045] FIG 4C illustrates a second variant of the third embodiment shown in FIG 4A which uses a multimode fiber 97 to deliver the laser beam 94 onto the workpiece 17, to collect the scattered object beam 100 and to combine the reference beam and object beam for generating the optical fringe signal 101. A Cassegrain optical system composed of a small reflector 95, a turning prism or small mirror, and a large aperture lens is used to couple the laser beam 94 into the multi-mode fiber 97. The laser beam exiting the fiber end 98 is focused by mean of a lens 99 onto the surface of workpiece 17. The scattered object beam 100, is then focused back into the multi-mode fiber 97. A fraction of the laser beam is also back reflected by the partially reflective fiber end 98, generating the reference beam. The reference beam and the object beam are combined together during the back propagation in the multi-mode optical fiber 97. The optical fringe signal 101 exiting back the optical fiber is then focused by mean of the lens 96 onto the array of detectors 102. The signals 103 are then processed by a parallel processing circuitry 104 similarly to the embodiment described in FIG 4A.

[0046] The processing circuit used for demodulation of quadrature signals is shown FIG 5, FIG 6 and FIG 7. FIG 5 describes a demodulation that gives an

output signal proportional to the displacement. The two in-quadrature signals 28 and 29 generated by the detectors 26 and 27 are both divided into high frequency signals 115 and 116 and low-frequency two signals 114 and 117 using low-pass filters 110 and 113 and high-pass filter 111 and 112. Cross-multiplication by mixers 118 and 119 is then performed to generate two out-of-phase displacement signals 120 and 121. For instance, displacement signal 120 corresponds to the multiplication by mixer 118 between the high-frequency signal 116 of detector 27 and the low-frequency signal 114 of detector 26. Similarly, displacement signal 121 corresponds to the multiplication by mixer 119 between the high-frequency signal 115 of detector 26 and the low-frequency signal 117 of detector 27. The said two out-of-phase displacement signals 120 and 121 are then subtracted by the differential amplifier 122 to produce the output signal 123 proportional to the displacement of the workpiece surface.

[0047] By changing the nature of the filtering before cross multiplication, the output signal can also be made proportional to the velocity of the workpiece surface. This is shown on FIG 6, where the in-quadrature signals 28 and 29 are both divided into the original signals and the derivative signals 126 and 127. Cross-multiplication by mixers 118 and 119 is then performed to generate two out-of-phase velocity signals 128 and 129. For instance, velocity signal 128 corresponds to the multiplication by mixer 118 between the derivative signal 126 of detector 26 and the signal 29 of detector 27. Similarly, velocity signal 129 corresponds to the multiplication by mixer 119 between the derivative signal 127 of detector 27 and the signal 28 of detector 26. The said two out-of-phase velocity signals 128 and 129 are then subtracted by the differential amplifier 122 to produce the output signal 130 proportional to the velocity of the workpiece surface.

[0048] A third demodulation scheme is shown in FIG 7 where the mixers 118 and 119 are no longer used for cross-multiplication, but they are used instead for squaring the high-frequency signals 133 and 134. The two in-quadrature



signals 28 and 29 generated by the detectors 26 and 27 are filtered to remove their low frequency components by the high-pass filters 131 and 132. the filtered signals 133 and 134 are then squared by mixer 118 and 119. The two squared signals 135 and 136 are then added into a summing amplifier 122 to produce the output signal proportional to the displacement energy 137, the square of the displacement, of the workpiece surface.

[0049] The three quadrature demodulations described in FIG 5, FIG 6 and FIG 7 lead to an output signal that is independent of the absolute phase of the optical fringe signals. The only requirement for stable, phase-independent signal is to have two in-quadrature signals. A variant of the demodulation scheme shown FIG 7 is shown in FIG 8. In FIG 8, the squaring of the filtered signals is now replaced by a rectification of the filtered signals. The in-quadrature signals 28 and 29 are both filtered with high-pass filters 138 and 139. The high-frequency signals 140 and 141 are then rectified using rectifiers 142 and 143. The two rectified signals 144 and 145 are then added by a summing amplifier 146 to produce the output signal 147 correlated to the absolute value of the displacement of the workpiece surface. With this demodulation scheme, the amplitude of the output signal 146 varies between 100% and 140% of its true value depending on the phase of the optical fringe signal. The use of rectification instead of multiplication gives a less accurate measurement, but it is simpler to implement electronically, and can be well adapted to some kinds of applications.

[0050] For the embodiments according to the invention described in FIG 4A, FIG 4B and FIG4C, in which the quadrature detection scheme is based on the random distribution of speckle. The demodulation carried out by the processing circuit is described in FIG 9A and FIG 9B. Here, single channel processing, not requiring cross-multiplication, is performed instead because in-quadrature signals are not available for these embodiments. The signal 149 from detector 148 is first filtered using a high-pass filter 150 and the high-

frequency signal **151** is then either squared using mixer **152** as shown in FIG 9A or rectified using rectifier **154** shown in FIG 9B.

[0051] Finally, for the embodiment described in FIG 3, where heterodyne detection scheme is used, the processing circuit is described in FIG 10. The heterodyne signal **157** is divided in two in-phase signals **159** and **160** by in-phase power divider **158**. The signal component **160** is first filtered by means of narrow-band filter **162** which rejects the sidebands, i.e. the ultrasonic signal modulation, and only keeps the carrier signal at frequency  $f_B$ . The carrier signal **164** is then delayed by phase shifter **163**. The value of the phase shift is adjusted such that the phase difference between the two signals **159** and **164** sent to the mixer **165** equals  $90^\circ$ . The signal component **159** is sent to the one of the port of the mixer **165** after being attenuated by attenuator **161** in order to match the amplitude of the carrier signal **164** that is sent to the other port of the mixer **165**. After the mixer, the low-pass filter **166** removes the signal components at  $2*f_B$  that was generated by the mixing process in order to only keep the low-frequency component of the signal **167** and corresponding to the ultrasonic displacement of workpiece surface.